Intelligent Mobility Research at Defence R&D Canada for Autonomous UGV Mobility in Complex Terrain

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ABSTRACT

The objective of the Autonomous Intelligent Systems Section of Defence R&D Canada – Suffield is best described by its mission statement, which is "`to augment soldiers and combat systems by developing and demonstrating practical, cost effective, autonomous intelligent systems capable of completing military missions in complex operating environments." The mobility requirement for unmanned ground vehicles operating in urban settings must increase significantly if robotic technology is to augment human efforts in these roles and environments. The intelligence required for autonomous systems to operate in complex environments demands advances in many fields of robotics. This has resulted in large bodies of research in areas of perception, world representation, and navigation, but the problem of locomotion in complex terrain has largely been ignored. In order to achieve its objective, the Autonomous Intelligent Systems Section is pursuing research that explores the use of intelligent mobility algorithms designed to improve robot mobility. Intelligent mobility uses sensing, control, and learning algorithms to extract measured variables from the world, control vehicle dynamics, and learn by experience. The primary focus of the paper is to present the research tools, topics, and plans to improve the autonomy and mobility of unmanned ground vehicles operating in urban settings to assist the Canadian Forces in future urban operations.

1.0 INTRODUCTION

The Autonomous Intelligent Systems Section (AISS) at Defence R&D Canada – Suffield (DRDC Suffield) envisions autonomous systems contributing to decisive operations in the urban battle space. In this vision, teams of unmanned ground, air, and marine vehicles (UAVs, UGVs, and UMVs) and unattended ground sensors (UGSs) will gather and coordinate information, formulate plans, and complete tasks, as envisioned in Figure 1. In this scenario higher altitude UAVs may supply coarse city maps to smaller more highly maneuverable UAVs, to construct streetscape information with sufficient information for UGVs to navigate city streets and build 3D world representation models of the urban battle space. On the ground, UGSs can be used to gather details of operational importance, but it will be the UGVs that will be called upon first to enter unknown city blocks if they are to keep soldiers out of harms way. They must navigate unknown highly complex environments in order to provide information with sufficient detail for tactical operations and contribution to real-time situational awareness. The objective of Defence R&D Canada's Cohort project is to demonstrate the capability for UxV teams to support urban operations in complex environments [1].

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Figure 1: Scenario illustrating teams of unmanned ground and air vehicles gathering and coordinating information, formulating plans, and completing tasks.

The autonomy of UGVs operating in urban settings must increase significantly if robotic technology is to augment human efforts in military relevant roles and environments. Creating effective intelligence for these systems demands advances in perception and world representation, navigation, and learning. In the land environment, these scientific areas have garnered much attention. However, the problem of locomotion in complex terrain has largely been ignored. The ability to develop robots that can operate in highly unstructured environments necessitates advances in visual processing and scene understanding, complex reasoning and learning, and dynamic motion planning and control. Moreover, a framework for reasoning and planning in these unstructured environments will likely require new mathematical concepts that combine dynamics, logic, and geometry in ways that are not currently available [2]. This undeveloped framework has resulted in a lack of control design tools for robotic locomotion and, as a result, practical applications have been limited. Advances have largely been confined to positioning and navigating within structured environments.

In order to move away from these structured environments and into the real world, UGVs need to interpret the environment more effectively. Novel platforms require detailed data to negotiate obstacles but their variable position and stance make it difficult to produce accurate geometric representations. In addition, geometric maps make gross assumptions about the environment. Thus, perception systems must be capable of systematically assessing the environment and adapting accordingly. To address the requirement for robotic locomotion in complex terrain, AISS is pursuing research that explores the use of a perception architecture which adapts to changing environments and intelligent mobility algorithms designed to improve robot mobility. Intelligent mobility research investigates sensing, control, and learning algorithms to extract measured variables from the world, to control vehicle dynamics, and to enable robotic systems to learn by experience. The algorithms seek to exploit available world representations of the environment and the inherent dexterity of the UGV to interact with its surroundings and produce locomotion in complex terrain. The objective of this research is to create effective intelligence to improve the mobility of ground-based mobile systems operating in urban settings to assist the Canadian Forces in their future urban operations.

2.0 INTELLIGENT MOBILITY RESEARCH METHODOLOGY

Intelligent mobility algorithms seek to exploit available world representations of the environment and the inherent dexterity of the platform to allow the UGV to interact with its surroundings and produce locomotion in complex terrain. Intelligent mobility uses control, sensing, and learning algorithms to control vehicle dynamics, extract measured variables from the world, and learn by experience. The development of a mobility platform is highly application dependent, making it difficult to develop systems for mission requirements that have a high degree of variability. Many of the traditional methods of analysis, modelling, and simulation prove too complex for representation of highly unstructured and complex environments. Moreover, few metrics have been developed for smaller, lighter UGVs to describe performance for operation in unstructured complex environments, which makes system optimization difficult [3].

The AISS research methodology addresses the numerous challenges and uncertainties that complicate UGV design [4]. Firstly, distinct vehicle paradigms were formulated in an attempt to conduct research that addresses the large complexities of relevant military UGVs. Next, vehicles were configured that represent each of the distinct paradigm classes, to achieve mobility using varying capabilities. The intent is not in the design of optimal robots for specific missions, but rather to allow research to occur in the many areas of mobility. The proposed research methodology produces a depth of research in intelligent mobility with activity in the areas of control, sensing, and learning. The methodology addresses the numerous challenges and uncertainties that complicate the design of UGV systems. These topics are discussed in further detail below.

3. DISTINCT MOBILITY PARADIGMS AND REPRESENTATIVE VEHICLES

The distinct mobility paradigms which describe the general classes of desired robotic vehicle behaviours include, but are not limited to: deliberate dexterous, variable geometry, and dynamic reactive locomotion. Real-world testing of intelligent mobility algorithms is being conducted using representative UGVs from each of the defined mobility paradigms. Experimentation using these UGVs will validate simulation models, and be used to investigate mobility behaviours. Their progress and research objectives are discussed below.

3.1 Deliberate Dexterous Mobility Paradigm

Interest in mobile robotics operating in complex environments and performing useful tasks is continuously expanding. Researchers in the mobile robotics community look towards biological systems for inspiration in design and control given their ability to maneuver in complex terrain. Mobile robots with increased dexterity that model biological systems have the potential to perform complex mobility tasks. High degree-of-freedom UGVs produce an expectation of animal-like performance. However, the high degrees-of-freedom result in an increased control requirement for the system. The UGV needs to be controlled both at the individual actuator and system level to achieve desired motion or position. The objective of research into high degree-of-freedom UGVs is to create a control theory that applies to a general class of mobile robotics. The deliberate dexterous paradigm represents a class of UGVs that requires advanced control strategies to control a large number of degrees-of-freedom. They operate by a deliberate placement of appendages that permit the UGV to traverse complex terrain with slow, confident maneuvers, as depicted in Figure 2. Research in the deliberate dexterous mobility paradigm is being addressed by the 14 degree-of-freedom hybrid legged/wheeled Micro Hydraulics Toolkit (MHT).

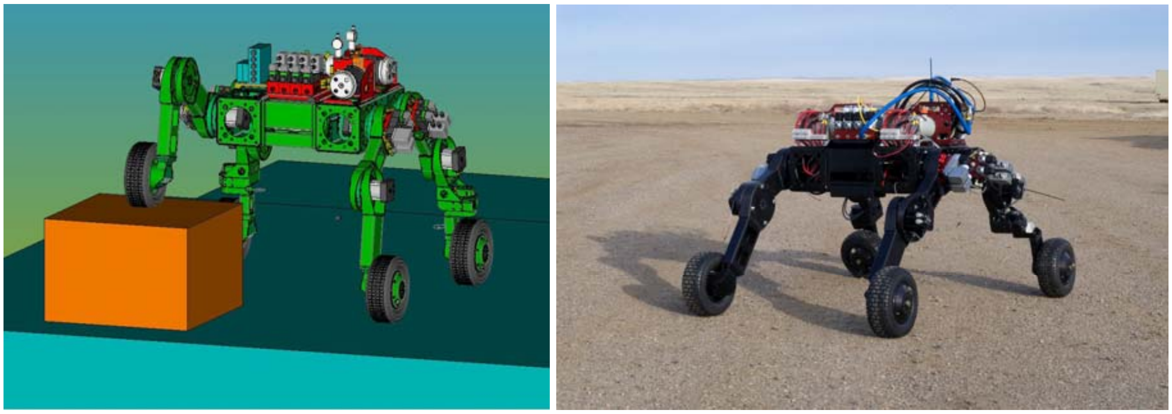

Figure 2: (left) CAD depiction of deliberate dexterous platform overcoming an obstacle. (right) MHT assembled in full configuration.

3.1.1 Deliberate Dexterous Vehicle: Micro Hydraulics Toolkit

The MHT vehicle is used to pursue intelligent mobility research in the deliberate dexterous mobility paradigm. The vehicle, shown in Figure 2, is a reconfigurable 14 degree-of-freedom platform that primarily uses hydraulic actuators. The UGV has a main structure that houses the pump, motor, battery, and control electronics. The main structure also houses a rotary actuator, or *hip*, that connects to another rotary actuator, or *knee*, by means of a structural leg member or *fibula*. The rotary *knee* actuator connects to a rotary wheel by another structural member or *tibia*. The four *hip* and four *knee* actuators are non-continuous rotary hydraulic actuators capable of 90º of rotation. The vehicle is intended to be reconfigurable and therefore the structural members connecting *hip* to *knee* and *knee* to wheel are designed to be fastened in 22.5º increments. The four hydraulic wheel actuators are capable of continuous rotary motion. The two electric wheel direction actuators are capable of 180º of rotation. Dimensions in the standing position are approximately one meter in length, width and height.

3.2 Variable Geometry Mobility Paradigm

The focus of the variable geometry mobility paradigm is to investigate mobility behaviours that exploit the shape-shifting capabilities of the UGV, depicted in Figure 3. Control of vehicle geometry via intelligent mobility algorithms can produce various modes of locomotion for the UGV (e.g. snow-shoeing, legged motion, tracked motion, etc.) and conformance to its environment to provide improved mobility (e.g. duct crawling, bridging gaps, ducking under obstacles, etc.). These UGVs rely on complex control strategies to take advantage of a relatively low number of degrees-of-freedom for performance. Research in the variable geometry mobility paradigm is being addressed using the Shape-shifting Tracked Robotic Vehicle (STRV).

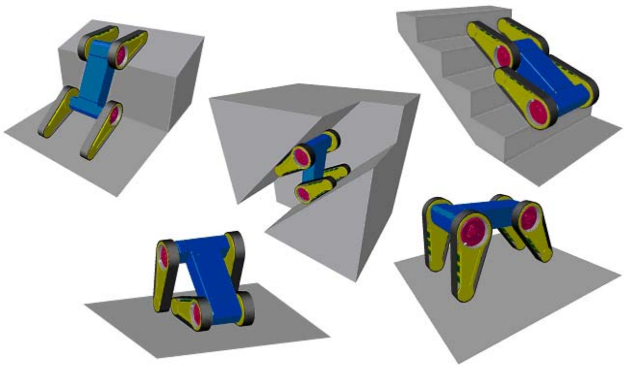

Figure 3: (left) Examples of various modes of locomotion and conformance to environment by the variable geometry platform concept. (right) STRV in motion.

3.2.1 Variable Geometry Vehicle: Shape-shifting Tracked Robotic Vehicle

The low degree-of-freedom STRV, illustrated in Figure 3, was conceptualized from the need for a simple system to initiate learning control algorithm research. The STRV consists of four independently driven tracks with solid axles articulating the front and rear pair of tracks. The axles are capable of 720º of rotation at a rate of 15º per second. The vehicle dimensions are 0.65m wide, 0.24m high and 1.32m long in its fully open configuration versus 0.72m in its closed configuration. It weights 42.3kg and can reach a maximum speed of 1.4m/s. Novel research applicable to operations in complex environments will be possible, taking advantage of the small size of the UGV, its robustness, its few degrees-of-freedom and its inherent ability to change geometry.

3.3 Dynamic Reactive Mobility Paradigm

The paradigm of dynamic reactive behaviours has the potential to greatly enhance the mobility of UGVs. This paradigm includes UGVs that utilize hybrid concepts of compliant legs and wheels, which store and release energy. These UGVs have the potential to yield mobility behaviours that widen the scope of negotiable obstacles and generally increase UGV mobility, which would not otherwise be possible with conventional configurations. As such, a smaller robot with intrinsic dynamic capabilities may prove to outperform larger conventional vehicles. They will require advanced control strategies and have a high dependency for perception and world representation to intelligently negotiate obstacles. They will likely require more sophisticated control strategies to exploit these behaviours. The Platform for Ambulating Wheels (PAW) UGV, depicted in Figure 4, will be used to investigate how the inherent dynamic capabilities of a UGV can be exploited to produce improved mobility characteristics.

Figure 4: (left) CAD design of dynamic reactive platform concept. (right) First implementation of a dynamically stable bounding gait on a hybrid wheeled-leg robot.

3.3.1 Dynamic Reactive Vehicle: Platform for Ambulating Wheels

The PAW robot consists of a T-shaped aluminum frame. The constructed PAW has dimensions of approximately 0.35m wide, 0.5m long, and 0.2m high. Its approximate weight is 19kgs. The actuated *hip* is connected to the wheel by a leg member. The leg member is made to be compliant by connecting leg segments with a pair of springs and limiting their motion in the axis that travels through the *hip* and wheel centre. The "hips" are driven by electric motors turning a toothed belt/pulley configuration, which are used for numerous legged-wheeled behaviours. The wheels are driven by electric motors turning bevelled gears, used for pure wheeled locomotion or in legged-wheeled behaviours for the vehicle. The PAW is controlled from a PC/104 running a real-time operating system. Power is supplied by an onboard 36 volt DC battery.

The PAW robot, pictured in Figure 4, is used in the study of both wheeled and dynamically stable legged modes of locomotion. UGV intelligence is created to exploit the hybrid nature of the UGV, to enhance the wheeled behaviour stability and locomotive performance of the robot. Recent experimental results regarding current wheeled mobility behaviours for the PAW, including a novel turning behaviour for the vehicle have been presented [5]. Furthermore, the first implementations of a dynamically stable bounding gait on a hybrid wheeled-leg robot have also been presented [6].

4.0 PERCEPTION FOR INTELLIGENT VEHICLES

Perception systems process sensor data into useful abstract representations of the environment allowing the UGV to plan its actions accordingly. Although significant progress has been made in the area of perception it remains one of the greatest challenges facing the robotics community. In particular, most practical perception systems suffer from the fact that they rely on geometric information and are hand crafted to work in limited and prescribed environmental situations. Further, the majority of perception systems have been developed with conventional wheeled platforms in mind. Intelligent mobility researchers have identified two key research areas, discussed further below, which need to be addressed to ensure the success of perception systems for novel platforms.

4.1 Localization and Pose Estimation

A problem common among UGVs is how to accurately register sensor measurements to a local or global frame of reference. Typically, the homogeneous transformations which govern this registration rely on accurate measurements between coordinate frames. The problem is further aggravated by issues including vehicle motion, timing issues, wheel slippage, and inaccurate pose estimation that can often cause sensor data to be registered incorrectly. Consider the STRV, depicted in Figure 3, attempting a complex maneuver. The platform consists of four independently driven tracks with a solid axle articulating the front and rear track pair. In such circumstances it is reasonable to assume that a large amount of slippage will occur. Consider also that the vehicle may be operating indoors without the assistance of GPS. Furthermore, as the vehicle actuates and changes its configuration the homogenous transforms governing sensor registration need to reflect the new platform configuration. In order to provide these transformations each vehicle must have a highly accurate internal representation of its configuration. All of these factors make traditional localization and sensor registration methods even more sensitive to error. An area of research which has the potential to alleviate these problems is Vision Based Simultaneous Localization and Mapping (VSLAM). These algorithms rely on vision based techniques to extract unique landmarks or features from visual imagery, which can be used to improve vehicle localization and mapping. Stereovision or stereo from motion are often used in conjunction with the feature detector to retrieve 3D structure of the environment. VSLAM has been successfully implemented in UGVs using both the Harris detector [7] and the Scale Invariant Feature Tracking (SIFT) algorithm developed by Lowe, though the SIFT algorithm has proved to be more robust to variations in scale, rotation, and lighting [8]. While many of VSLAM implementations utilize odometry as an input to predict motion, successful implementations have been developed that estimate this motion by tracking features through several video frames, matching corresponding features, and estimating the motion necessary to bring these matched features into alignment [9, 10]. In these cases, visual data from the camera need not be registered to a common frame of reference and thus sensor registration issues are alleviated. The AISS program currently has a contract in place to deliver a VSLAM implementation from a monocular camera deliverable in 2007 at which point evaluation on novel platforms can be assessed.

4.2 Learning the Environment

Perception systems for UGVs seek to provide an accurate and robust representation of the environment. This representation should provide information necessary to allow the UGV to make an informed decision. While the majority of fielded systems provide only a geometric representation of the environment, it is noted that perception systems may also incorporate image segmentation, object recognition, and feature identification in order to provide further *context* to the environment. As UGVs progress from simplistic to more complex environments, reliance on purely geometric information is not feasible. It is essential to augment these representations with contextual information such as general object and materials recognition.

Learning systems play a key role in adapting conventional perception systems to allow better situational awareness. For example, Stanford's Stanley [11] improves the accuracy of its traversability map by using a learning system that maintains a mixture of Gaussians model of driveable terrain. Similarly, the Learning Applied to Ground Robotics (LAGR) program [12] has shown the benefit that learning can have on vehicle performance. A number of key perception capabilities where learning will play a key role for intelligent mobility platforms have been identified.

4.2.1 Environmental Recognition

One weakness of traditional UGVs is that they have been designed to operate under a specific set of

environmental conditions. This makes algorithms brittle when the environment changes. A goal of intelligent mobility research is to allow the UGV to expand its range of operational environments and to be able to transition between them seamlessly. For instance, a UGV may be expected to travel from a rural environment into an indoor environment. The vehicle may then have to enter a building, collect imagery and return to its command position. Since the algorithms necessary to navigate properly in each environment are so different, the UGV must continually assess the environment and adapt its perception system accordingly.

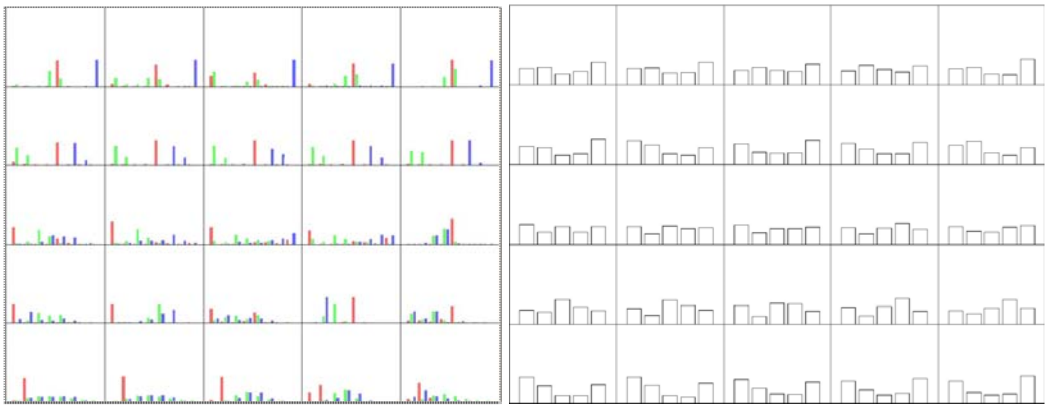

Figure 5: The HSV color histogram and orientation histogram calculated for each subimage. This data is used as input to a neural network classifier.

Currently, AISS researchers are using computer vision and neural network learning to determine whether an UGV is indoor or outdoor. A monocular camera is first segmented into 5x5 subimages which allows the neural network to learn important spatial characteristics. Features are periodically extracted from these subimages and used as input to a single layer feed forward neural network. Features, such as those illustrated in Figure 5, currently being investigated include HSV, LUV, RGB color histograms, first and second order color moments, orientation and curvature histograms, and wavelet histograms. The output layer contains one neuron which classifies the image as either indoor or outdoor. Successful classification rates between 85-95% are typical depending on network configuration and training data.

4.2.2 Recognition and Modelling of Relevant objects

In order for novel platforms to interact appropriately with their environment, they must be capable of recognizing objects that may affect their behaviour. Object recognition has enjoyed a long history in the realm of computer vision and robotics. For instance, systems have been developed that can accurately recognize roads [13], concertina wire [14], water [15], faces [16], etc., that may significantly impact how a UGV behaves in their presence. Even more significant is the recognition of objects, which the UGV may be able to traverse through intelligent mobility. In these cases, it is not sufficient to simply recognize an object, but to also model its physical characteristics such as shape, coefficients of friction and restitution.

AISS is currently exploring object recognition and modelling for stair climbing using a nodding laser. To extract the structural information of each scanline image, edges are located using edge-based detectors for a 1D signal. Slopes and flat areas are identified using region-based detectors looking for homogeneous regions. Finally, the detected segments are connected to generate the final segmentation. The resulting segmentation provides more useful structural information for robot control navigation compared to the initial range data.

A two stage reinforcement learning approach is being investigated, which will automatically adapt vehicle configuration as it approaches the stairs. The first control layer inputs the terrain map into a reinforcement learning algorithm for axle position computation. Reinforcements are provided based on vehicle motion progress and pitch stability of the platform. The training target commands are obtained from data collected during remotely controlled runs to train the system by passive observation. A second layer selects behaviours based on obstacle recognition from image segmentation and surface generation. While current efforts are focussed on stair climbing, the approach may be extended to other basic objects.

4.2.3 Learned Trafficability and Locomotion

The area of terrain classification and learned trafficability has received much attention in recent years. Programs such as the LAGR program have shown the effectiveness of inferring terrain characteristics from visual data. AISS has been applying machine learning to its Raptor class UGV (small Ackerman steered truck) to learn trafficability characteristics and geometry estimates of terrain that cannot be directly sensed. This work marks an important first step in using on-board learning systems to associate terrain appearance with trafficability characteristics rather than specified hand crafted solutions. AISS is extending this work into the area of legged locomotion in complex terrains. Boston Dynamics' Little Dog robot and DARPA's complex surrogates, both shown in Figure 6, will serve as the development platform.

Figure 6: (left) Little Dog Platform (right) Complex Terrain Surrogate (Courtesy of Boston Dynamics)

Learning locomotion will require combined efforts in many fields and is viewed as the definitive challenge in fielding learning systems in real world situations. Learning locomotion will require control of a high degree of freedom vehicle in partially known, highly irregular environment where many relevant states and features are very difficult to define. It will require learning to interpret the unstructured terrain from imagery, range scans and foot/terrain interactions within the context of moving a small legged vehicle. The robot will determine appropriate footfalls and recognize obstacles types that require adaptation or new control strategies to surmount them. Control of the Little Dog will require simultaneous discovery and learning in continuous domains of actuator control and discrete representations of leg phasing. The world itself also needs to be represented across both continuous and discrete domains in ways that are accessible, usable, expendable and adaptable by the control systems. This work will include, trial and error learning (reinforcement), demonstration based learning, optimal control, machine vision, reasoning and planning.

4.3 Perception Architecture

The capabilities discussed in Section 4 are computationally expensive and thus it is unreasonable to run all these processes concurrently. There exists a need to mediate between representations and adapt the perception system to fill the needs of the platform. The systematic dynamic selection and arbitration of perception behaviours remains an open area of research which AISS is addressing.

The proposed perception architecture [17] includes a perception arbitration and selection module called the Perception Mediation Module (PMM). The purpose of the PMM is to assign perception techniques to specifically address the perceptual needs of the UGV. It was hypothesized that the perceptual needs of a UGV should be determined based on four significant factors. The first is sensor reliability, where sensors that are believed to be behaving unreliably are given less weight in sensor fusion. The next is environmental complexity, whereby UGVs operating in complex outdoor environments should utilize different perception algorithms than UGVs in indoor environments. Next are the mobility characteristics of the UGV, which are used to determine perceptual needs and system parameters. Lastly, mission awareness may dictate specific perceptual needs such as the generation of a 3D map.

Furthermore, these factors are interdependent and may sometimes be at odds. As such, a novel approach to select the optimum set of perception techniques is necessary, see Figure 7. This is similar to the control arbitration problem used for robot navigation. Development of this architecture is ongoing as part of the environmental recognition research discussed in Section 4.2.1. As more behaviours are developed the perception architecture will necessarily grow with it.

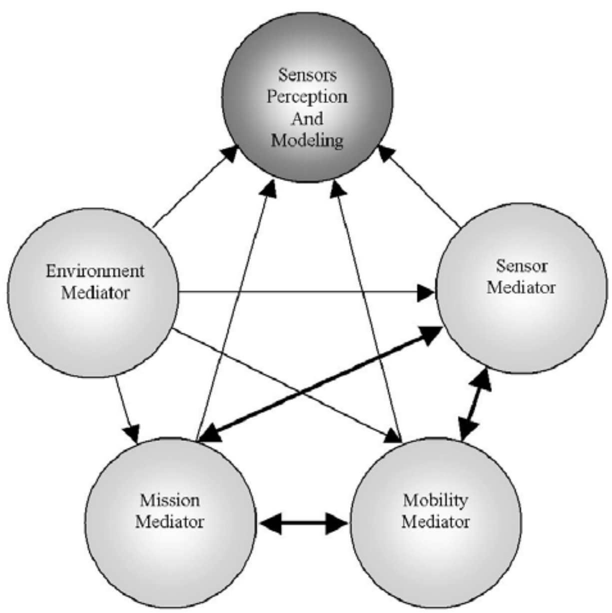

Figure 7: The Perception Mediation Framework constantly assesses its perceptual needs and changes its perception strategy. This is done by assessing the perceptual needs from sensor, mobility, environment, and mission points of view.

5.0 CONTROL FOR INTELLIGENT MOBILITY

Mobile robotic vehicles are often innovative and simple in their design. They exploit various modes of locomotion to address their environment and objective. In spite of these efforts their practical application remains a challenge, primarily due to the fact that it is difficult to plan for, coordinate and control all of the required vehicle degrees-of-freedom.

5.1 Intuitive and Systematic Controller Synthesis

Human scripted algorithms prove difficult and time consuming to understand, design, and tune for diverse UGVs that often possess multiple modes of locomotion. No unified framework exists for this problem. This is primarily due to the fact that robotic vehicles are examples of underactuated nonlinear systems for which few general solutions to the problem exist in the control community.

> *While many of the theoretical elements needed for the systematic derivation of a theory for underactuated nonlinear control systems are known, they have not been widely and methodically studied from a practical perspective. Consequently, control of underactuated nonlinear systems remains an endeavour of the theoretician and not a practical tool of the engineer [18].*

Work in this area by Vela [18] is seen as a significant first step towards the development of a systematic procedure for understanding the control-theoretic and dynamical properties of underactuated nonlinear systems. It is necessary to investigate these types of systematic approaches while thinking ahead to the idea of adaptable algorithms that will lead to emergent behaviours. Application of intuitive and systematic controller synthesis for underactuated nonlinear systems may provide considerable insight and understanding of locomotive control systems.

5.2 Sensing for Purposeful Locomotion in Complex Terrain

Algorithms to control vehicle dynamics and behaviours must be mated with relevant perceptual information of the environment to allow the UGV to interact intimately with its surroundings. For the most part, use of open-loop behaviours, which do not close the control loop with world representation information, are unable to meaningfully maneuver UGVs in the world. For a closed-loop system, perceptual information must be made available to the controller. However, there exists a disconnect between the information provided by perception systems and that which is required by the locomotion system for controller synthesis. Mathematical models are essential in the analysis and design of traditional control systems and prove to be indispensable tools to the controls engineer. The next logical extension would be to embed a mathematical modeller in an autonomous system. In this context, AISS is using Vortex by CMLabs Simulations Inc., a faster than real-time physics based engine, to act as an on-board modelling tool. To fill the gap between the real-world and the controller, relevant geometric features of the environment are extracted into a world representation, whose coordinates are passed to the mathematical modeller. A model of the UGV that includes its dynamics is then correctly positioned into this world model, as illustrated in Figure 8. This model now contains sufficient information represented in a meaningful mathematical framework that can be used by the intelligent mobility algorithms. The controller synthesis may be performed in faster than real-time allowing for trials of candidate behaviours before implementation. The controller is able to formulate input/output relationships, calculate and make corrections to behaviour implementation for robust performance.

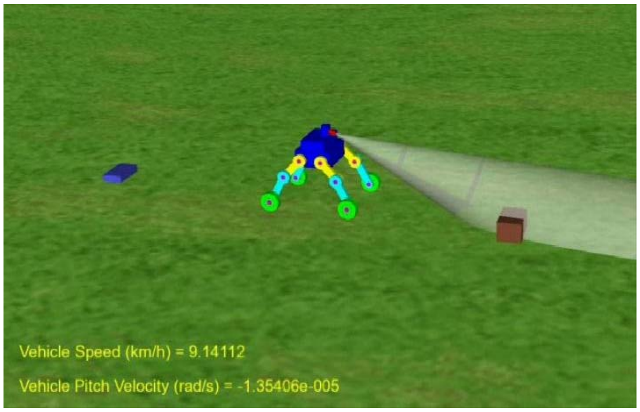

Figure 8: Model of the Micro Hydraulic Toolkit (MHT) in a representation of its environment based on relevant geometric features.

5.2.1 Measured Variables from Complex Environments for Locomotion

In the practical application of control theory, the control engineer must determine what variables should be controlled and those variables that should be measured in an effort to make the system behave in a desired manner. The selection of measurement variables should be those that have strong relationships with the controlled outputs and are dependent on the control objective, which may be the stabilization of an unstable plant, rejection of disturbances and/or to track reference changes. For traditional control problems such as temperature control, automobile cruise control or flight controls, these relationships are fairly intuitive. These relationships are also fairly intuitive in some of the inner control loops of a robotic platform that control motor torque for leg position or wheel speed.

These control concepts become more abstract at higher levels where control is needed to produce desired robotic behaviours that yield improved mobility characteristics. Here, intelligent mobility algorithms must select what variables should be measured from the world in an effort to move the UGV successfully through its environment. As an example, perception algorithms may produce a 3D model of the environment. Intelligent mobility algorithms must then extract relevant information from this data to be useful. This information must be translated into a meaningful mathematical framework that can be used by the intelligent mobility algorithms. The variables measured from the environment will change depending on the specific UGV, and are complicated by vehicle speed, modes of locomotion, and mobility objectives. Specific examples of measured variables may include footfall distances for galloping, gap crossings for jumping, hill grades for energy management, or clearances for shape-shifting maneuvers. For example, during the course of its approach as depicted in Figure 9, the PAW must calculate the footfalls necessary to store and release the required energy at just the right time and place to enable it to jump onto the ledge. The capability of faster than real-time calculations allow for corrections to motion or selection of alternate behaviours due to disturbances such as uneven surfaces or variable surface frictions.

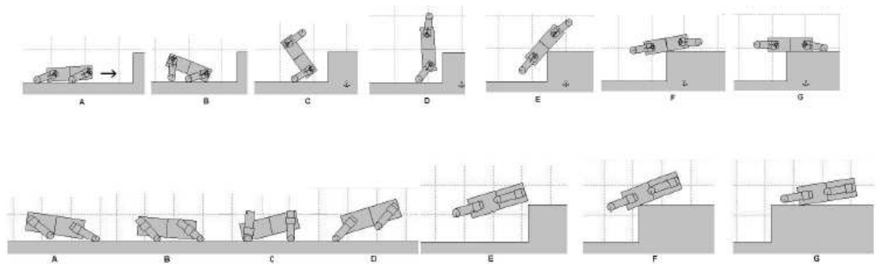

Figure 9: PAW Vehicle Behaviour: Simulation results that investigate various PAW behaviours used to jump onto a high ledge.

CONCLUSION

The Autonomous Intelligent Systems Section at Defence R&D Canada – Suffield envisions autonomous systems contributing to decisive operations in the urban battle space. The effective intelligence for these systems operating in complex environments demands advances in many fields that have resulted in large bodies of research, while largely ignoring the problem of locomotion in complex terrain. Development of perception systems for highly mobile novel platforms has largely been ignored. Moreover, traditional control theory and tools are ill-equipped for new robotic demands for autonomous operation in unknown complex environments. This paper documents the progress and future direction of intelligent mobility research to address this gap. Distinct mobility paradigms are identified that address a spectrum of mobility issues, challenges and uncertainties that complicate UGV mobility. These paradigms facilitate research in areas of control, sensing, and learning necessary to create intelligent mobility algorithms for robotic locomotion in complex terrain. The objective is to produce improved UGV locomotion for military relevant environments to better address the needs of the Canadian Forces in their future urban operations.

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